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Prospect theory in an evolutionary game: Construction of watershed ecological compensation system in Taihu Lake Basin

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A B S T R A C T

As an important system to solve cross regional water pollution, watershed ecological compensation has been widely used in the world. However, the existing studies mainly focus on the governments, while ignoring the important role of polluting enterprises in watershed ecological compensation. Thus, the established watershed ecological compensation mechanism is difficult to implement sustainably. Therefore, taking the local governments and polluting enterprises in the watershed as the research object, and studying the change process and influencing factors of their decision-making behavior is of great significance to attract polluting enterprises to join the watershed ecological compensation, and to formulate a sustainable watershed ecological compensation mechanism to solve the cross regional water pollution. Therefore, based on prospect theory and evolutionary game theory, this paper firstly establishes an evolutionary game model between local governments and polluting enterprises in Taihu Lake Basin; secondly, combined with simulation technology, their decision-making behaviors and influencing factors of watershed ecological compensation are studied. The results show that: (1) The initial probabilities will affect their decision-making behaviors; (2) The ecological compensation fee has little influence on the decision-making behaviors of polluting enterprises; (3) The increase of environmental tax rate has significant influence on the local governments' decision-making behaviors with low initial probabilities; (4) The improvement of supervision ability can promote local governments and polluting enterprises to reach a stable state faster; (5) The marginal decreasing degree of value function has a stronger influence on local governments than on polluting enterprises. This paper can provide suggestions for local governments to build a sustainable watershed ecological compensation mechanism including polluting enterprises, and provide the scientific basis for decision-makers of polluting enterprises whether to join watershed ecological compensation.

1. Introduction

Since ancient times, the river basin has always been the birthplace of civilization and the center of economy (Olli and Pertti, 2001). In ancient times, due to the relative backwardness of science and technology, the ability of human beings to use the natural resources within the basin was limited, so the impact of human

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beings on the ecological environment of the basin was also small (Ahmed, 2002). However, in modern times, the rapid development of science and technology has greatly improved the ability of human beings to use natural resources in the river basin. Meanwhile, with the rapid increase of population, the pollution of natural environment in the basin is further intensified (Cai, 2008). Because of the cumulative effect of pollution, the pollution of water resources in the basin has exceeded its self-purification capacity (Schwarzenbach et al., 2010), which has led to a large number of water pollution events in the world (Er-Ping et al., 2010; Wilhelm et al., 2011; Zhao, 2009).

Due to the large influence range of the river basin and the numerous stakeholders involved, the pollution of water resources by any stakeholders is easily transferred to other areas through the flow of water bodies (Chang et al., 2017). Therefore, the water pollution in a river basin usually crosses multiple regions and becomes a cross regional pollution problem (Tanaka and Nakayama, 2010; Yu, 2011). According to the theory of sustainable development, all stakeholders in the basin have the same right to use water resources and discharge certain pollutants. Due to the different demands of different stakeholders for water resources and different behaviors of sewage discharge, it is difficult to coordinate stakeholders to protect the water environment in the basin. In order to solve this problem, countries around the world have tried various measures, such as enacting environmental protection laws (Kamminga, 1995), developing clean energy (Benchekroun and Chaudhuri, 2014; Eloy et al., 2012), collecting sewage charges (Zhao et al., 2013), etc., but these measures cannot mobilize the enthusiasm of stakeholders in the basin, and then form a positive feedback mechanism to actively protect the water environment of the basin. Therefore, the short-term effect is significant, but it cannot be implemented for a long time. On this basis, watershed ecological compensation emerges, which provides a new way to coordinate the relationship between different stakeholders in the basin, and then jointly solve the problem of cross regional water pollution (Higgins et al., 2014).

Watershed ecological compensation comes from payment of ecosystem services (Pan et al., 2017; PRC, 2014). It is a system that encourages different stakeholders to jointly protect the water environment in the basin by means of voluntary transaction between ecosystem products and service providers and consumers and government transfer payment (Farley and Costanza, 2010; Pagiola et al., 2005; Xu et al., 2016). Due to the advantages of watershed ecological compensation in the protection of water environment, it has been used by many countries in the world (Feng et al., 2018). The current research on watershed ecological compensation takes the administrative region governments in the upstream and downstream areas as the research object, and the compensation funds are paid by them. This kind of watershed ecological compensation will bring about the following two disadvantages: first, for developing countries, the point source pollution produced by polluting enterprises is the main source of water pollution in river basins. However, pollution-based enterprises are rarely included in the study of watershed ecological compensation, and the key research objects are ignored. Secondly, the river basin water pollution control needs to pay a lot of money. If we rely on the governments for a long time, it will produce a lot of financial pressure on the governments; at the same time, it will squeeze the governments' investment in other aspects. If the pollution-oriented enterprises in the basin are not included in the research scope, the funds brought by the enterprises to control water pollution will be lost. The above two disadvantages will restrict the effective solution of water pollution problems. Therefore, in order to formulate a reasonable watershed ecological compensation mechanism, it is necessary to bring the polluting enterprises into the research framework. Meanwhile, it is of great significance to explore the decision-making behavior mode and their influencing factors between local governments and polluting enterprises in watershed ecological compensation, which is of great significance for the governments to attract pollution-based enterprises to join the watershed ecological compensation and how to coordinate the relationship between the governments and pollution-based enterprises. This is also a key issue to build a reasonable and long-term implementation of the watershed ecological compensation mechanism and effectively solve the cross regional water pollution.

The research on watershed ecological compensation is mainly divided into three parts: compensation concept and theory research (Engel et al., 2008; Tacconi, 2012; Wunder, 2005; Wunder et al., 2008), compensation mechanism research (Dai, 2010; Sheng and Webber, 2018; Sheng et al., 2017; Yang et al., 2018) and compensation effect evaluation research (Lu et al., 2018; Sun et al., 2016; Xiong and Jiang, 2012), in which the compensation mechanism research is the core. The determination of the subject and object of watershed ecological compensation and the analysis of its influencing factors is an important part of the compensation mechanism, which directly affects whether watershed ecological compensation mechanism can be implemented sustainable (Gao et al., 2019; Hao Li et al., 2018). For this study, firstly, scholars mainly identify the upstream and downstream governments as the compensation subject and object from a macro perspective, and then study the changes of their decision-making behavior and influencing factors in the process of watershed ecological compensation (Chen et al., 2014; Guo et al., 2013; Xie et al., 2013). Few scholars study the polluting enterprises and the governments as the compensation subject and object simultaneously, which is a defect for the theory of watershed ecological compensation. Secondly, if the decision-making behavior of the compensation subject and object and their influencing factors are concentrated between the governments, the real pollution producing enterprises will be ignored, and the constructed watershed ecological compensation mechanism is difficult to be implemented sustainable due to the lack of the participation of polluting enterprises. Finally, scholars basically take the actual utility of compensation subject and object as the basis of decision-making behavior analysis. However, due to the implementation of watershed ecological compensation will bring a certain degree of risk to the participants, there is a certain deviation in using the actual utility for risk decision-making, and the expected utility should be used for research.

Therefore, in order to fix these research gaps, this paper takes the local governments and polluting enterprises in the Taihu Lake Basin of China as the research object, combines the prospect theory and evolutionary game theory to build a game model between them, and makes an in-depth study on their decision-making behavior and main influencing factors of watershed ecological compensation. Firstly, this paper analyzes the economic development and pollution situation of Taihu Lake Basin, and determines the necessity and urgency of constructing watershed ecological compensation mechanism in this area. Secondly, this paper combines prospect theory and evolutionary game theory to build a game model based on the local governments and polluting enterprises in Taihu Lake Basin. Thirdly, by solving the model, this paper studies the change of decision-making behavior of both sides in watershed ecological compensation. Finally, combined with numerical simulation technology, the main factors affecting their decision-making behavior are analyzed.

The main contributions of this paper are as follows: (1) from the micro point of view, it is of great significance to bring polluting enterprises into the analysis framework of watershed ecological compensation, which is of great significance to improve the traditional watershed ecological compensation theory which takes the governments as the research object only. (2) This paper explores the change process and main influencing factors of decision-making behavior between local governments and pollution-based enterprises in watershed ecological compensation, which will provide an important reference for the relevant policy makers of watershed ecological compensation in various countries, and can effectively include the polluting enterprises in the process of policy-making, so as to effectively reduce the water pollution and protect the water environment. (3) Based on the expected utility (the perceived utility for profits and losses) of different participants, an evolutionary game model of watershed ecological compensation between local governments and polluting enterprises in Taihu Lake Basin is constructed. It can effectively improve the scientificity of the decision-making behavior analysis of the subject and object of watershed ecological compensation by introducing psychology and risk into the decision-making analysis. The research results of this paper can provide the governments with a more perfect watershed ecological compensation mechanism including polluting enterprises, and then provide the basis for decision-makers of polluting enterprises whether to join the watershed ecological compensation.

The paper proceeds as follows. Section 2 introduces the theoretical basis of this paper – Prospect Theory and evolutionary game theory. Section 3 proposes the research area and model construction. Section 4 makes simulation experiment and result analysis. Section 5 discusses the results, states the limitations and summarizes future works. Section 6 gets conclusions and offers suggestions.

2. Literature review of theories

2.1. Prospect theory

The prospect theory was jointly proposed by Professor Daniel Kahneman and Amos Tversky (Kahneman and Tversky, 1979). They applied the comprehensive observation from the field of psychological research to economics and made outstanding contributions to human judgment and decision-making in uncertain situations (Tversky and Kahneman, 1992). According to the hypothesis of rational economic man used in economics for a long time, they reveal the irrational psychological factors that affect the choice behavior from the perspective of human psychological characteristics and behavior characteristics (Booij et al., 2010; Nicholas, 2012).

The prospect theory holds that the characteristics of individual's choice in the risk situation are inconsistent with the basic principles of utility theory in classical economics. And the human decision-making process is divided into two stages, the first stage is to collect and sort out all kinds of information related to random events; the second stage is to comprehensively evaluate the above information and make decisions (Giorgi and Hens, 2006; Gurevich et al., 2009). In summary, the content of prospect theory mainly includes the following three parts:

(1) People not only pay attention to the absolute amount of wealth, but also pay more attention to the change of wealth;
(2) When facing profits, people are risk averse; when facing losses, they are risk preference ;
(3) People's judgment of profits and losses is often based on the reference point.

In addition, the two professors made a quantitative study of the prospect theory and put forward a famous value function model, as shown in equation (1).

$$v(\Delta U) = \begin{cases} (\Delta U)^n, & \Delta U \geq 0 \\ -\lambda \times (-\Delta U)^n, & \Delta U < 0 \end{cases} \tag{1}$$

Where ΔU represents the deviation of profits or losses spread based on the reference point; when $\Delta U>0$, it means that the decision maker's psychological perception of the random event is profits, and when $\Delta U<0$, it indicates that the decision maker's psychological perception of the random event is losses; $v(\Delta U)$ represents the perceived utility when people are uncertain about the profits or losses of random events; n represents the marginal decreasing degree of the value function of perceived profits and losses for the decision makers ($n \in (0, 1)$), and with the increase of n, decision makers tend to take risk; λ indicates people's avoidance degree of losses, and with the increase of λ, the decision makers are more disgusted with losses.

According to the above analysis, the research on watershed ecological compensation mechanism should include both polluting enterprises and local governments, so as to establish a long-term implementation of compensation mechanism. This mechanism has a certain degree of risk to them. For polluting enterprises, if they join in watershed ecological compensation to protect water resources, they can get part of compensation fee from local governments to reward their protection behavior. However, due to the instability of policies or the failure to compensation fee, polluting enterprises may not obtain this fee. Meanwhile, in order to reduce pollution, polluting enterprises may increase production costs by improving technology or replacing sewage treatment equipment, which will bring great pressure on enterprises. On the contrary, if polluting enterprises do not join in watershed ecological compensation, they will face the fine of the local governments and legal sanctions. Similarly, for local governments, if they pay compensation fee, there will be additional financial pressure on them. Meanwhile, whether polluting enterprises can really implement emission reduction is uncertain. On the contrary, if local governments do not pay compensation fee, it will not be able to complete the task of protecting the water resources issued by the superior government. Therefore, when constructing the watershed ecological compensation mechanism, both polluting enterprises and local governments will face risks. In order to obtain their maximum utility, they should take the expected utility as a reference instead of the actual utility. Because prospect theory clearly explains the decision-making process of human beings in the risk situation, it is just suitable for analyzing the risk decision-making process of each participant in watershed ecological compensation.

2.2. Evolutionary game theory

As an important branch of game theory, evolutionary game theory differs from classical game theory in the following aspects: first, evolutionary game theory holds that the players are bounded limited, not completely rational (Kaniovski and Young, 1995; Schmidt, 2004; Taylor and Jonker, 1978). The reason is that people's cognition, perception and expression are limited. Secondly, evolutionary game theory takes population as the research object, and individuals can gradually modify their strategies in the process of multiple games through observation, learning and other ways, and finally achieve a stable state for all players (Perera, 2018; Ritzberger and Weibull, 1995). The complete analysis framework of evolutionary game theory mainly includes the following three parts: the payoffs of game matrix, the replicated dynamic system and the evolutionary stability strategy (Schmidt, 2004).

(1) The payoffs matrix. It means that under the different strategy combination of all the players, we can determine their

respective payoffs and express them in the form of matrix, which is the basis of evolutionary game analysis.

(2) The replicated dynamic system. The replicated dynamic system consists of the replicated dynamic equation, which is the mapping relationship between the strategy chosen by each player and the fitness. Fitness is a basic concept derived from the theory of biological evolution. It can be understood as the growth of the number of individuals who choose a certain strategy after a game (Friedman, 1998a).

(3) The evolutionary stability strategy. Evolutionary stability strategy embodies the concept of equilibrium in game theory, which means that different players can gradually adjust their strategies through observation, learning and imitation in the process of multiple games, and finally make different players reach a stable state. When all players have reached a stable state, the strategy combination chosen by each player is called evolutionary stable strategy (Cressman and Apaloo, 2016).

In watershed ecological compensation, the local governments and the polluting enterprises have different interest needs. For polluting enterprises, they hope to maximize their profits by increasing production capacity; but for local governments, they hope not only that the local economy can grow rapidly, but also that the ecological and social benefits within their jurisdiction can be maintained. Besides, there are a large number of individuals in the two groups. When faced with risk, these individuals will make a comparison between the perceived utility of the possible profits and losses and the utility of reference point, and finally make decisions according to the comparison results. Because the two groups show different interest demands, there is a game between them on the water protection. Due to the limited rationality, it is difficult for them to find the best strategies in one game. Instead, they need to observe the behaviors of other individuals and then make choice. Only after many games can they gradually find the best strategies. The process of finding the best strategy is in line with the analytical framework of evolutionary game theory, so the theory can be used to study the construction of watershed ecological compensation mechanism.

In conclusion, because both prospect theory and evolutionary game theory are based on the premise of bounded rationality, the combination of these two theories can not only reflect the decision-making psychology of local governments and polluting enterprises for uncertain profits and losses, but also dynamically describe their strategic selection process. Simultaneously, combined with the simulation technology, the influence of different factors on their strategy selection can be visualized. Therefore, in the watershed ecological compensation of Taihu Lake Basin, it is appropriate to use prospect theory and evolutionary game theory to study the changes of decision-making behavior and influencing factors of local governments and polluting enterprises.

3. Study area and model

3.1. Study area

Taihu Lake Basin is located in the south of the Yangtze River Delta, which includes Jiangsu Province (Suzhou City, Wuxi City and Changzhou City), Zhejiang Province (Jiaxing City, Huzhou City and part of Hangzhou City), Shanghai City (mainland part, excluding Chongming, Changxing and Hengsha island) and Anhui Province (part of Xuancheng City) (Fig. 1). The total drainage area is 36900 km^2, of which Jiangsu, Zhejiang, Shanghai and Anhui account for 52.6%, 32.8%, 14.0% and 0.6% respectively (Resources, 2019). Taihu Lake Basin, with superior natural conditions and convenient land and water transportation, is the most densely populated and economically dynamic area in China's large and medium-sized cities. According to the statistics of Taihu Basin Authority, at the end of 2018, the total population of Taihu Lake Basin is 61.04 million, accounting for 4.4% of the total national population; the GDP is 8766.3 billion yuan, accounting for 9.7% of the national GDP; the per capita GDP is 144000 yuan, 2.2 times of the national per capita GDP (Resources, 2019). Because the industrial structure of the major cities in the Taihu Lake Basin is characterized by "industry > service industry > agriculture", the pollution in the Taihu Lake Basin is dominated by point source pollution, supplemented by non-point source pollution.

Due to the rapid economic development and population migration, the local water pollution problem is becoming increasingly serious, and lead to serious water pollution events, such as cyanobacteria events. It led to the serious deterioration of water quality in Wuxi City, Jiangsu Province, and affected the normal water use of the whole city (Zhang et al., 2010). After the outbreak of this incident, the Chinese government pay more attention to the water environment in the Taihu Basin, and began to pilot the establishment of the watershed ecological compensation system to solve the cross regional water pollution in this region (Dai, 2014; PRC, 2017, 2018). In Taihu Lake Basin, Jiangsu Province, Zhejiang Province, Anhui Province and Shanghai city have established the watershed ecological compensation system of each province and municipality respectively. Although watershed ecological compensation system of Taihu Lake Basin has been implemented for many years, and it also plays a positive role in the protection of water resources, many problems are still found in the process of practice, such as the misappropriation of ecological compensation fee by part of the local governments; When watershed ecological compensation system is established, the participation of polluting enterprises was not considered. These problems restrict the effective implementation of ecological compensation system in Taihu Lake Basin.

3.2. Model

3.2.1. Hypothesis

Before constructing the evolutionary game model between the polluting enterprises and the local governments in Taihu Lake Basin, we need to make the following hypothesis:

(1) In Taihu Lake Basin, local governments and polluting enterprises are limited rational players, which means that they can not determine their own optimal strategies in one game, but can find their own optimal strategies in multiply games.

(2) In the Taihu Lake Basin, there are two strategies for the polluting enterprises. One is to protect water resources of the basin and use new sewage treatment technology; the other is not to protect water resources of the basin and continue to use the original sewage treatment technology.

(3) In the Taihu Lake Basin, the local governments also have two strategies to choose, which are to pay ecological compensation fee to polluting enterprises and not to pay ecological compensation fee to polluting enterprises.

(4) The rights and obligations of the local governments are equal. When the local governments choose to pay the ecological compensation fee, they also have the right to supervise polluting enterprises and collect the environmental protection tax; when the local governments choose not to pay, they also lose the right to supervise polluting enterprises and collect the environmental protection tax.

(5) According to the prospect theory, there is no difference between perceived value and actual utility between the two

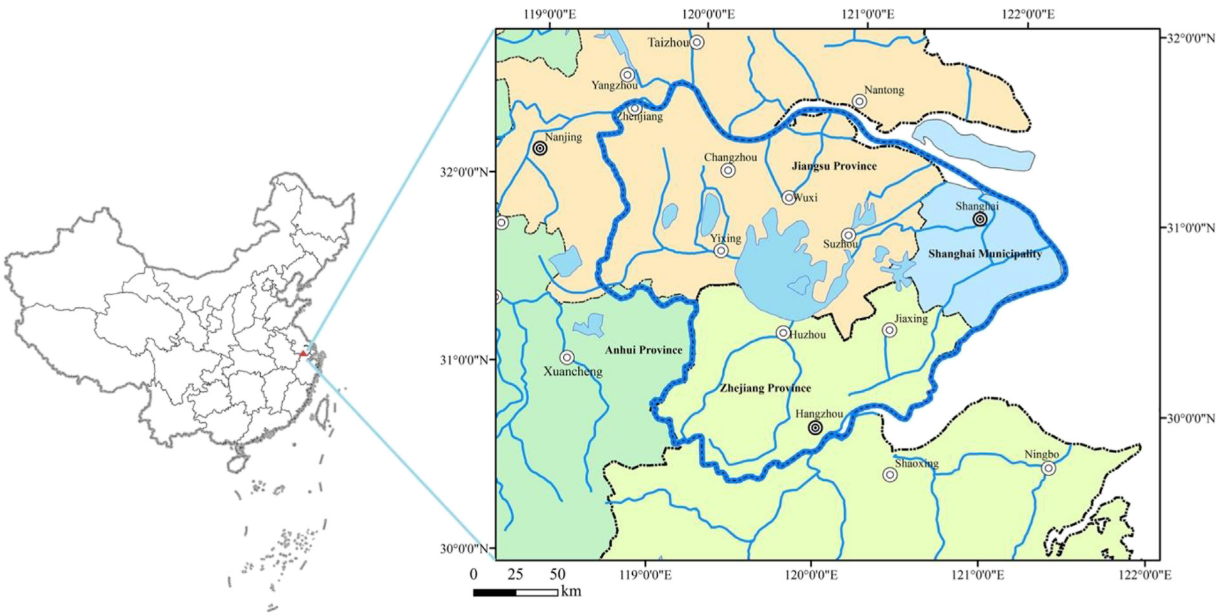

Fig. 1. The study area of Taihu Lake Basin in China.

players of the game for the determined profits and losses; when the players are uncertain about the profits or losses, there is a difference between perceived value and actual utility.

(6) According to prospect theory, the value of reference point in value function is set to 0. And the perceived utility of the random event is replaced by the deviation of profits or losses and the reference point.

3.2.2. Evolutionary game model of two-party players based on the prospect theory

3.2.2.1. Variables. In the two-party game of local governments and polluting enterprises, there are several variables. All of variables are positive and they are defined as follows:

R: The total income of polluting enterprises when they choose not to protect the water resources of the Taihu Lake Basin and continue to use the original sewage treatment technology;

R_1: The total income of polluting enterprises when they choose to protect the water resources of Taihu Lake Basin and use new sewage treatment technology;

T: The total investment cost which polluting enterprises implement new sewage treatment technology in order to protect water resources in the Taihu Lake Basin, mainly including the cost of basic equipment purchase, maintenance and staff training;

L: Ecological compensation fee, which is paid by local governments to polluting enterprises to make up for the sacrifices made by the polluting enterprises to protect the water resources in the Taihu Lake Basin;

E: The environmental tax base when the polluting enterprises choose not to protect the water resources of Taihu Lake Basin and continue to use the original sewage treatment technology;

E_1: The environmental tax base when the polluting enterprises choose to protect the water resources of Taihu Lake Basin and use the new sewage treatment technology;

K: The cost of local governments' supervision on polluting enterprises' emission behaviors;

H: The social benefits of local governments due to the improvement of water environment in Taihu Lake Basin caused by the reduction of pollutant discharge;

F: The fines imposed by local governments on polluting enterprises when they discharge excessive sewage;

D: Reputation loss suffered by local governments due to poor water environment in Taihu Lake Basin;

b: Environmental tax rate;

m: The supervision ability of local governments to find out the excessive discharge of sewage by polluting enterprises;

g: The proportion of local governments' actual payment to polluting enterprises of ecological compensation fee allocated by the central government.

3.2.2.2. Payoffs of different players. In the study of watershed ecological compensation in Taihu Lake Basin, there are four possible strategies combination because local governments and polluting enterprises have two strategies to choose.

(1) When the polluting enterprises choose to protect water resources and adopt new technologies to reduce sewage discharge, and the local government chooses to pay compensation fees, polluting enterprises need to pay the cost of new technology, and they need to pay sewage charges to discharge sewage in the production process; meanwhile, the ecological compensation fee given by the governments to the enterprises is an additional income for the polluting enterprises. As the environmental tax rate and the payment proportion of ecological compensation fee will change with the policy, the two players should use the expected value function to measure it. The specific benefits are as follows:

The payoff of polluting enterprises is shown in equation (2):

$$R_1 - T + v(g \times L) + v(-b \times E_1) \quad (2)$$

Where R_1 refers to the total income of polluting enterprises when they choose to protect the water resources of Taihu Lake Basin and use new sewage treatment technology. T refers to the total investment cost of new technology. $v(g \times L)$ represents the perceived utility of polluting enterprises on ecological compensation fee because the ecological compensation fee is a psychological profit for polluting enterprises.L and g represent ecological compensation fee and its payment proportion respectively. By comparison, $v(-b \times E_1)$ represents the perceived utility of polluting enterprises on the environmental tax because the environmental tax paid by polluting enterprises is a psychological loss for them. E_1 and b represent the environmental tax base when enterprises choose to protect water resources and the environmental tax rate of Taihu Lake basin.

The payoff of local governments is shown in equation (3):

$$v(-g \times L) + v(b \times E_1) - K + H \tag{3}$$

Where $v(-g \times L)$ represents the perceived utility of local governments on ecological compensation fee because it is a psychological loss for local governments. And $v(b \times E_1)$ represents the perceived utility of local governments on the environmental tax because the environmental tax is a psychological benefit for local governments. K and H represent the supervision cost of local governments and the social benefits of local governments respectively.

(2) When polluting enterprises don't protect water resources and continue to use original sewage treatment technology, local governments choose pay the compensation fee, polluting enterprises will also discharge sewage and need to pay sewage charges, but the standard charged will be higher than that when protecting water resources; And polluting enterprises will also face the punishment of local governments because they do not protect water resources. Whether the punishment can be implemented depends on the local governments' supervision ability. Because the sewage charges and punishment are a possible expenditure for the polluting enterprises, but it is a possible income for local governments and the environmental tax rate and supervision ability will change with the policy, so we need to use the value function to measure them. The specific benefits are as follows:

The payoff of polluting enterprises is shown in equation (4):

$$R + v(-b \times E) + v(-m \times F) \tag{4}$$

Where R represents the total income of enterprises when they choose not to protect water resources of Taihu Lake basin. $v(-b \times E)$ represents the perceived utility of polluting enterprises on the environmental tax because the environmental tax paid by polluting enterprises is a psychological loss for polluting enterprises. $v(-m \times F)$ represents the perceived utility of polluting enterprises on the fine imposed by local governments on polluting enterprises when local governments find that polluting enterprises have discharged excessive pollutants, and it is a psychological loss for them. F and m refers to the fines and supervision ability of local governments.

The payoff of local governments is shown in equation (5):

$$v(b \times E) + v(m \times F) - K \tag{5}$$

Where $v(b \times E)$ represents the perceived utility of local governments on the environmental tax because the environmental tax paid by polluting enterprises is a psychological benefit for local governments. And $v(m \times F)$ represents the perceived utility of local governments on the fine and it is a psychological benefit for local governments.

(3) When polluting enterprises choose to protect water resources and use new technology to reduce sewage discharge, local governments choose not to pay the compensation fee.

The payoff of enterprise is as follows:

$$R_1 - T \tag{6}$$

The payoff of local governments is as follows:

$$H \tag{7}$$

(4) When polluting enterprises don't protect water resources and use original technology, local governments choose not to pay the compensation fee.

The payoff of polluting enterprises is defined as follows:

$$R \tag{8}$$

The payoff of local governments is defined as follows:

$$-D \tag{9}$$

Where D refers to the reputation loss of local governments due to poor water environment in Taihu Lake Basin.

The payoffs matrix of two-party players evolutionary game based on the prospect theory is listed in Table 1.

3.2.2.3. Replicated dynamic equation. For polluting enterprises, it is assumed that the probabilities of protecting water resources and using new sewage treatment technology of Taihu Lake Basin are x, and the probabilities of choosing not to protect the water resources and not using new technology are 1-x. Similarly, for the local governments, the probabilities of choosing to pay the ecological compensation fee to the polluting enterprises are y, while the probabilities of choosing not to pay the ecological compensation fee are 1-y. And U_{mn} refers to the expected payoffs of different players choosing different strategies, and $\overline{U_m}$ refers to the average payoffs of different players. m represents different players, $m = 1$ refers to the polluting enterprises, and $m = 2$ refers to the local governments; n refers to the different strategies for different players, where $n = 1$ refers to the first strategy, and $n = 2$ refers to the second strategy. The specification of each symbol is listed in Table 2.

According to the methodology of evolutionary game theory, the expect payoffs and average payoffs of different players under different strategies can be calculated. The specific calculation is as follows:

For polluting enterprises, the payoffs are:

$$U_{11} = y \times [-T + v(g \times L) + v(-b \times E_1)] + (1 - y) \times (R_1 - T) \tag{10}$$

$$U_{12} = y \times [R + v(-b \times E) + v(-m \times F)] + (1 - y) \times R \tag{11}$$

$$\overline{U_1} = x \times U_{11} + (1 - x) \times U_{12} = x \times \{y \times [-T + v(g \times L) + v(-b \times E_1)] + (1 - y) \times (R_1 - T)\} + (1 - x) \times \{y \times [R + v(-b \times E) + v(-m \times F)] + (1 - y) \times R\} \tag{12}$$

Where U_{11} and U_{12} represent the expect payoffs that polluting enterprises choose to protect or not to protect the water resources

Table 1
The payoffs of two-party players evolutionary game based on prospect theory.

		Local governments			
		Paying for compensation fee		Not paying for compensation fee	
Enterprise	Protecting water resources	$R_1 - T + v(g \times L) + v(-b \times E_1)$	$v(-g \times L) + v(b \times E_1) - K + H$	$R_1 - T$	H
	Not protecting water resources	$R + v(-b \times E) + v(-m \times F)$	$v(b \times E) + v(m \times F) - K$	R	$-D$

Notes: R represents the total income of enterprises when they choose to protect water resources of Taihu Lake basin; R_1 represents the total income of enterprises when they choose not to protect water resources of Taihu Lake basin; T represents the total investment cost; L represents ecological compensation fee; E represents the environmental tax base when enterprises choose not to protect water resources of Taihu Lake basin; E_1 represents the environmental tax base when enterprises choose to protect water resources of Taihu Lake basin; K represents the supervision cost of local governments; H represents the social benefits of local governments; F represents the fines; D represents the reputation loss of local governments; b represents the environmental tax rate; m represents he supervision ability of local governments; grepresents The proportion of local governments' actual payment to enterprises of ecological compensation fee; v represents the value function.

Table 2
The specification of each symbol.

Symbol	Description
x	The probabilities that enterprises choose to protect water resources in Taihu Lake Basin
$1\text{-}x$	The probabilities that enterprises choose not to protect water resources in Taihu Lake Basin
y	The probabilities that local governments choose to pay ecological compensation fee
$1\text{-}y$	The probabilities that local governments choose not to pay ecological compensation fee
U_{11}	The expect payoffs that enterprises choose to protect water resources in Taihu Lake Basin
U_{12}	The expect payoffs that enterprises choose not to protect water resources in Taihu Lake Basin
U_{21}	The expect payoffs that local governments choose to pay ecological compensation fee
U_{22}	The expect payoffs that local governments choose not to pay ecological compensation fee
$\overline{U_1}$	The average payoffs of enterprises
$\overline{U_2}$	The average payoffs of local governments

in the Taihu L*ake* Basin. $\overline{U_1}$ represents the average payoffs of polluting enterprises.

According to U_{11}, U_{12} and $\overline{U_1}$, the replicated dynamic equation of polluting enterprises can be calculated and the result is shown in equation (13).

$$F_1(x) = dx/_{dt} = x \times (x-1) \times \{R - R_1 + T - y \times [v(g \times L) + v(-b \times E_1) - v(-b \times E) - v(-m \times F)]\} \tag{13}$$

For local governments, the payoffs are:

$$U_{21} = x \times [v(-g \times L) + v(b \times E_1) - K + H] + (1-x) \times [v(b \times E) + v(m \times F) - K] \tag{14}$$

$$U_{22} = x \times H + (1-x) \times (-D) \tag{15}$$

$$\overline{U_2} = y \times U_{21} + (1-y) \times U_{21} = y \times \{x \times [v(-g \times L) + v(b \times E_1) - K + H] + (1-x) \times [v(b \times E) + v(m \times F) - K] + (1-y) \times [x \times H + (1-x) \times (-D)] \tag{16}$$

Where U_{21} and U_{22} represent the expect payoffs that local governments choose to pay or not to pay ecological compensation fee. $\overline{U_2}$ represents the average payoffs of local governments.

Similarly, based on U_{21},U_{22} and $\overline{U_2}$, the replicated dynamic equation of local governments can be calculated and it is shown in equation (17).

$$F_2(y) = dy/_{dt} = y \times (y-1) \times \{(x-1) \times D + x \times H - x \times [H - K + v(-g \times L) + v(b \times E_1)] + (x-1) \times [v(b \times E) + v(m \times F) - K]\} \tag{17}$$

By combining equations (12) and (16), we can obtain the replicated dynamic system of the two-party evolutionary game model, which is shown in equation (18).

$$\begin{cases} F_1(x) = dx/_{dt} = x \times (x-1) \times \{R - R_1 + T - y \times [v(g \times L) + v(-b \times E_1) - v(-b \times E) - v(-m \times F)]\} \\ F_2(y) = dy/_{dt} = y \times (y-1) \times \left\{ \begin{array}{l} x \times [D + K + v(-g \times L) - v(b \times E_1) + v(b \times E) + v(m \times F) - K] \\ +[K - D - v(b \times E) + v(m \times F)]\} \end{array} \right. \end{cases} \tag{18}$$

According to the basic hypothesis of evolutionary game theory, we can realize that the players are not complete rationality, but limited rational. It means that they cannot choose the best strategies in a game and they will change their own strategies over time. When the players go through multiple games and don't change their strategies, the replicated dynamic system is stable. The strategies combination of all players in a stable state is evolutionary stability strategies (ESS).

3.2.2.4. Evolutionary stability strategies. In order to get the stable state and ESS of this replicated dynamic system, we just set equation (18) equal to 0, which is shown in equation (19).

$$\begin{cases} F_1(x) = {dx}/{dt} = x \times (x-1) \times \{R - R_1 + T - y \times [v(g \times L) + v(-b \times E_1) - v(-b \times E) - v(-m \times F)]\} = 0 \\ F_2(y) = {dy}/{dt} = y \times (y-1) \times \Big\{x \times [D + K + v(-g \times L) - v(b \times E_1) + v(b \times E) + v(m \times F) - K] \\ \qquad +[K - D - v(b \times E) + v(m \times F)]\Big\} = 0 \end{cases} \tag{19}$$

Before solving equation (19), we need to set the initial values of the two players, which are *x(0)* and *y(0)*. And to solve equation (19), we can get five equilibrium points, which are $E_1(0,\ 0)$, $E_2(0,\ 1)$, $E_3(1,\ 0)$, $E_4(1,\ 1)$, $E_5(x^*,\ y^*)$. $E_5(x^*,\ y^*)$ can be obtained by solving equation (20).

$$\begin{cases} \{R - R_1 + T - y \times [v(g \times L) + v(-b \times E_1) - v(-b \times E) - v(-m \times F)]\} = 0 \\ \{x \times [D + K + v(-g \times L) - v(b \times E_1) + v(b \times E) + v(m \times F) - K] + [K - D - v(b \times E) + v(m \times F)]\} = 0 \end{cases} \tag{20}$$

The results of equation (20) are as follows:

$$\begin{cases} x^* = \dfrac{D - K + v(b \times E) + v(m \times F)}{D - v(-g \times L) - v(b \times E_1) + v(b \times E) + v(m \times F)} \\ y^* = \dfrac{R - R_1 + T}{v(g \times L) + v(-b \times E_1) - v(-b \times E) - v(-m \times F)} \end{cases} \tag{21}$$

equilibrium point is ESS. Taking the coordinates of points (E_1 to E_4) into Jacobine matrix of this system, we can get the Jacobian matrices corresponding to these four points, which are expressed as J_1 to J_4 and shown in equation (22)–(25).

$$J_1 = \begin{pmatrix} R_1 - R - T & 0 \\ 0 & v(b \times E) - K + v(m \times F) + D \end{pmatrix} \tag{22}$$

$$J_2 = \begin{pmatrix} R - R_1 + T & 0 \\ 0 & v(-g \times L) - K + v(b \times E_1) \end{pmatrix} \tag{23}$$

$$J_3 = \begin{pmatrix} v(g \times L) + v(-b \times E_1) - v(-b \times E) - v(-m \times F) - R + R_1 - T & 0 \\ 0 & K - v(b \times E) - v(m \times F) - D \end{pmatrix} \tag{24}$$

$$J_4 = \begin{pmatrix} T - v(g \times L) - v(-b \times E_1) + v(-b \times E) + v(-m \times F) + R - R_1 & 0 \\ 0 & K - v(-g \times L) - v(b \times E_1) \end{pmatrix} \tag{25}$$

Although we get five equilibrium points by replicated dynamic equation, we need to introduce new conditions to judge whether these five equilibrium points are the final stable points of the system. Based on the basic attributes of evolutionary stability strategy proposed by Friedman, evolutionary stability strategy must satisfy the pure strategy Nash equilibrium, while other forms' Nash equilibrium are not likely to be the stability strategy in the system (Friedman, 1998b). Thus, $E_5(x^*,\ y^*)$ represents mixed strategy Nash equilibrium, so it cannot be the final stable point of the system. In order to judge whether other 4 points are the stable points, we introduce the Lyapunov's System Stability Theory (Vadali and Kim, 2015). According to the theory, the eigenvalues of the corresponding matrix of a system can help to judge the stability of the system. If all eigenvalues of the matrix are negative, the system is stable; If all eigenvalues of the matrix are non-positive, and the eigenvalues equaling to 0 do not have multiple roots, the system is determined to be stable in the Lyapunov; otherwise, the system is not stable (Bomze and Weibull, 1995; Wang, 1966).

Based on the above analysis, we can calculate the Jacobian matrix of the system, which can be used to determine whether the

In line accordance with J_1 to J_4, we can find that a_{11} of J_3 and J_4 are opposite to each other (a_{11} refers to the eigenvalue shown in the first row and the first column of the matrix), the same to the a_{22} of J_4 and J_2 (a_{22} refers to the eigenvalue shown in the second row and the second column of the matrix). It means that if $E_4(1,\ 1)$ is a stable point, then $E_2(0,\ 1)$ and $E_3(1,\ 0)$ cannot be stable point; and vice versa. The same thing happened between $E_1(0,\ 0)$ and $E_2(0,\ 1)$.

By comparing the eigenvalues of these four points, only $E_4(1,\ 1)$ is the best result. In this case, polluting enterprises choose to protect water resources and use new sewage treatment technology, while the local governments choose to pay ecological compensation fee. This is also in line with the dominant idea of Taihu Basin for watershed ecological compensation system, so this paper will mainly discuss this state.

When E_4 is the final stable point, all its eigenvalues must be negative. Therefore, the model needs to be added the inequality group (26) as the constraint condition.

$$\begin{cases} T - v(g\times L) - v(-b\times E_1) + v(-b\times E) + v(-m\times F) + R - R_1 < 0 \\ K - v(-g\times L) - v(b\times E_1) < 0 \end{cases} \tag{26}$$

4. Simulation results

4.1. Initial probabilities

According to the above analysis, we can find that the initial probabilities of different players will affect the players' choice of strategies, and then affect the final stable state of the system. Therefore, in order to reflect the influence of the initial probabilities of different strategies chosen by the players on the replicated dynamic system, we simulate the initial probabilities randomly, and they are between 0 and 1. In addition to the initial probabilities, the settings of other variable values are listed in Table 3 and satisfy the constraints of inequality (26). Under the constraint of inequality group (26), we can get the change processes of strategy choice for different players under different initial probabilities. The result is shown in Fig. 2.

Based on Fig. 2, we can find that both initial probabilities of polluting enterprises and local governments will affect the time of the replicated dynamic system reaching the stable state. With the increase of the initial probabilities of the players, the time for the system to reach stable state is shorter. In order to illustrate the details, we divide the initial probabilities into two groups: high probabilities group and low probabilities group. In the high probabilities group, the initial probabilities of polluting enterprises and local governments are 0.6 and 0.8 respectively; in the low probabilities group, the initial probabilities of two players are 0.2 and 0.4 respectively.

(1) In the high probabilities group, $x(0) = 0.6$ and $y(0) = 0.8$. The changing process of replicated dynamic system is shown in Fig. 3(a). From Fig. 3(a), we can find that the initial probabilities cannot affect the final state of the system and they can only affect the time of the system reaching the stable state. Although the initial probabilities of the polluting enterprises are lower than that of the local governments, the speed of polluting enterprises reaching stable state is faster than that of the local governments. This shows that in the high probabilities group, the sensitivity of polluting enterprises to the initial probabilities is higher than that of the local governments.

(2) In the low probabilities group, $x(0) = 0.2$ and $y(0) = 0.4$. The changing process of replicated dynamic system is shown in Fig. 3(b). From Fig. 3(b), we can find that the change of initial probabilities will not affect the final stable state of the system. However, in the low probabilities group, it takes longer for the polluting enterprises to reach the stable state than the local governments. This is the opposite of the high probabilities group.

From simulation about the initial probabilities, it is clear that under the current constraints, the system will eventually stabilize

Table 3
The settings of variable values in the simulation of different initial probabilities.

Variable	R	R_1	T	L	E	E_1	K	H	F	D	b	m	λ	n	g
Value	40	50	9	3	150	120	5	5	3	15	0.1	0.5	1.2	0.88	0.5

Notes: R represents the total income of enterprises when they choose to protect water resources of Taihu Lake basin; R_1 represents the total income of enterprises when they choose not to protect water resources of Taihu Lake basin; T represents the total investment cost; L represents ecological compensation fee; E represents the environmental tax base when enterprises choose not to protect water resources of Taihu Lake basin; E_1 represents the environmental tax base when enterprises choose to protect water resources of Taihu Lake basin; K represents the supervision cost of local governments; H represents the social benefits of local governments; F represents the fines; D represents the reputation loss of local governments; b represents the environmental tax rate; m represents he supervision ability of local governments; λ represents people's avoidance degree of losses; n represents the marginal decreasing degree of the value function; $g$represents the proportion of local governments' actual payment to enterprises of ecological compensation fee; v represents the value function.

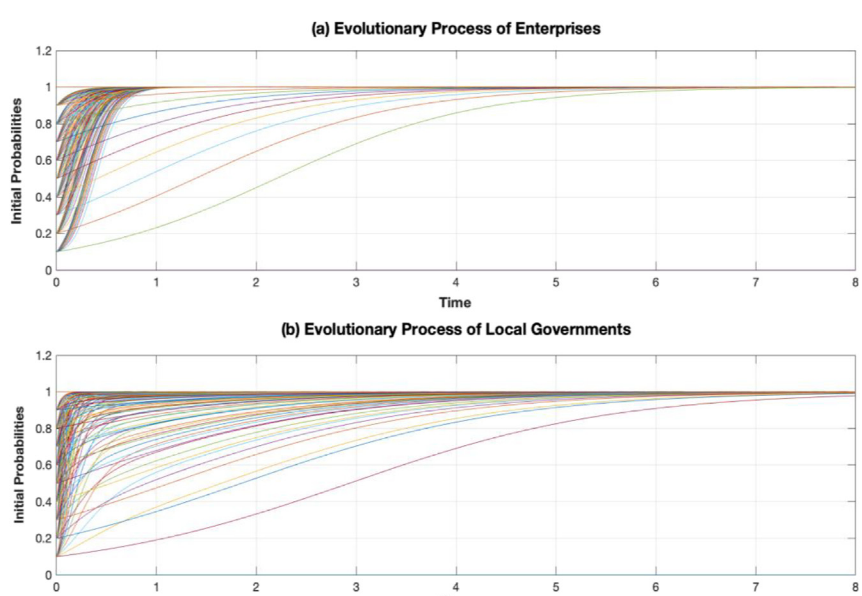

Fig. 2. Evolutionary Process of different players under different initial probabilities.

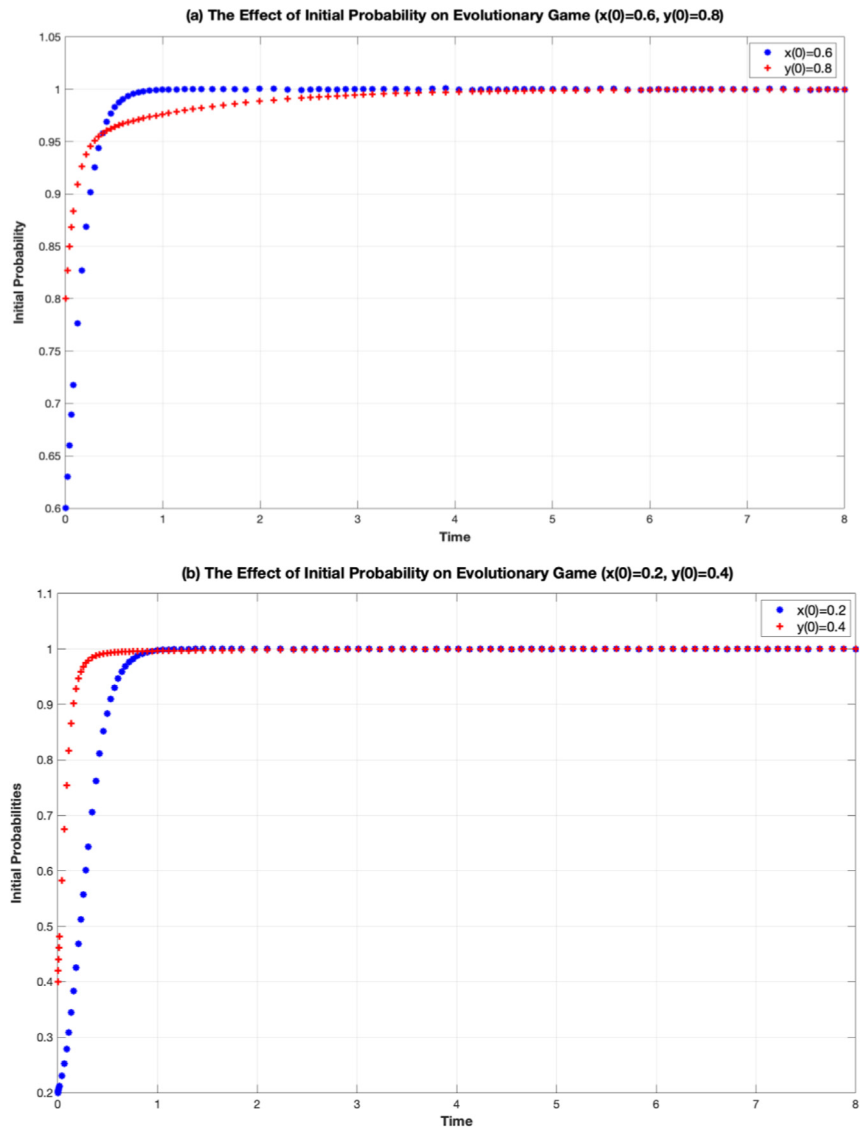

Fig. 3. The Effect of Initial Probabilities on Evolutionary Game (*x(0)* refers to the initial probabilities of enterprises; *y(0)* refers to the initial probabilities of local enterprises).

Table 4
The settings of variable values in the simulation of the ecological compensation fee.

Variable	R	R_1	T	E	E_1	K	H	F	D	b	m	λ	n	g
Value	40	50	9	150	120	5	5	3	15	0.1	0.5	1.2	0.88	0.5

Notes: R represents the total income of enterprises when they choose to protect water resources of Taihu Lake basin; R_1 represents the total income of enterprises when they choose not to protect water resources of Taihu Lake basin; T represents the total investment cost; E represents the environmental tax base when enterprises choose not to protect water resources of Taihu Lake basin; E_1 represents the environmental tax base when enterprises choose to protect water resources of Taihu Lake basin; K represents the supervision cost of local governments; H represents the social benefits of local governments; F represents the fines; D represents the reputation loss of local governments; b represents the environmental tax rate; m represents he supervision ability of local governments; λ represents people's avoidance degree of losses; n represents the marginal decreasing degree of the value function; grepresents the proportion of local governments' actual payment to enterprises of ecological compensation fee; v represents the value function.

at state 1, and will not change with the different initial probabilities. In this situation, the polluting enterprises choose to protect the water resources of Taihu Lake Basin and use new sewage treatment technology and the local governments choose to pay ecological compensation fee to the polluting enterprises. This is the best result we hope to get in the watershed ecological compensation of Taihu Lake Basin.

4.2. Ecological compensation fee

In order to reflect the effect of the ecological compensation fee on the replicated dynamic system, we take the ecological compensation fee and initial probabilities as the variables and simulate the system. The settings of other variable values in the system are listed in Table 4. Under the setting of variable values, the changing process of replicated dynamic system is shown in Fig. 4.

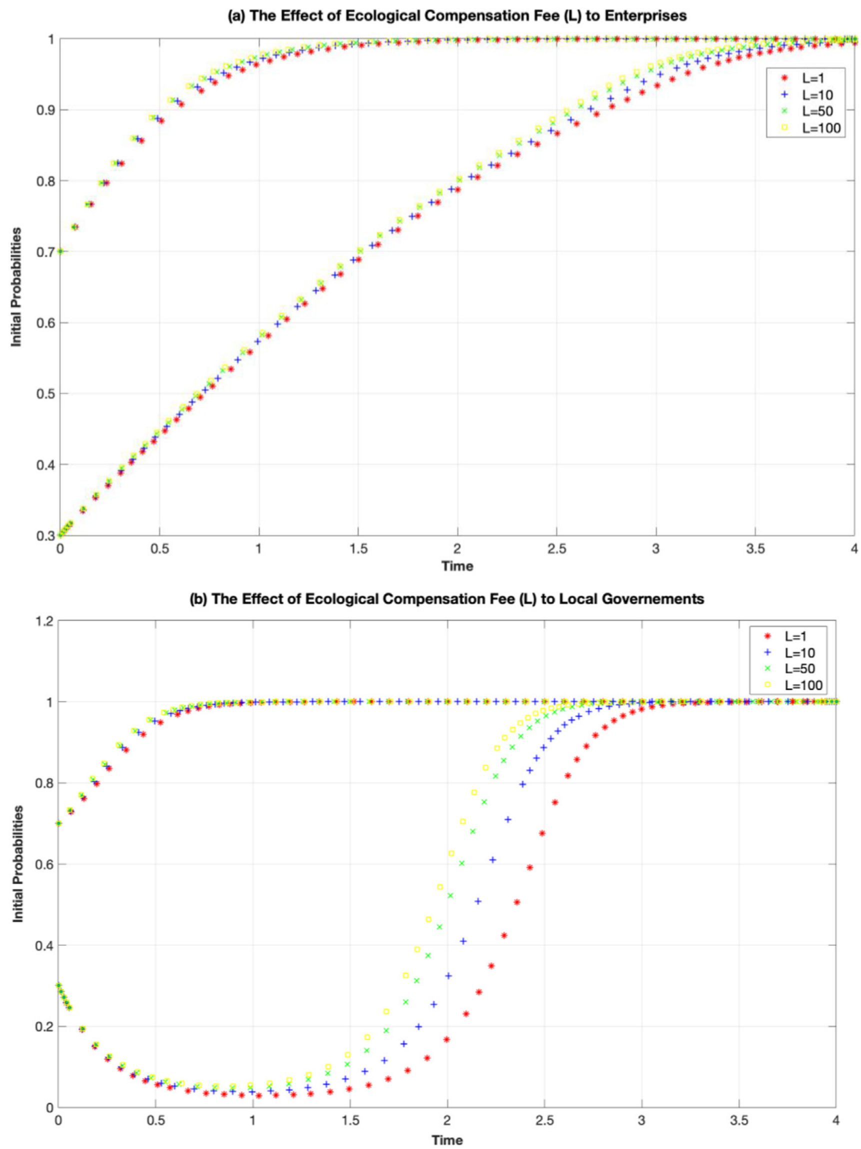

Fig. 4. The Effect of Ecological Compensation Fee (L) to Enterprises in the Two-party Evolutionary Game (L represents ecological compensation fee).

Table 5
The Settings of Variable Values in The Simulation of The Environmental tax Rate.

Variable	R	R_1	T	E	E_1	K	H	F	D	L	m	λ	n	g
Value	40	50	9	150	120	5	5	3	15	3	0.5	1.2	0.88	0.5

Notes: R represents the total income of enterprises when they choose to protect water resources of Taihu Lake basin; R_1 represents the total income of enterprises when they choose not to protect water resources of Taihu Lake basin; T represents the total investment cost; L represents ecological compensation fee; E represents the environmental tax base when enterprises choose not to protect water resources of Taihu Lake basin; E_1 represents the environmental tax base when enterprises choose to protect water resources of Taihu Lake basin; K represents the supervision cost of local governments; H represents the social benefits of local governments; F represents the fines; D represents the reputation loss of local governments; m represents he supervision ability of local governments; λ represents people's avoidance degree of losses; n represents the marginal decreasing degree of the value function; $g$represents the proportion of local governments' actual payment to enterprises of ecological compensation fee; v represents the value function.

From Fig. 4, we can find that although the ecological compensation fee changes, the system will eventually stabilize in state 1. At this time, the polluting enterprises choose to protect water resources and use new sewage treatment technology, while the local governments choose to pay ecological compensation. However, the effect of ecological compensation on polluting enterprises is different from that of local governments. For polluting enterprises, under different initial probabilities, by observing the trend of the curve, we can judge that the larger the ecological compensation fee is, the shorter the time for polluting enterprises to reach a stable state is. But on the whole, the increase of ecological compensation fee has little effect on the polluting enterprises. In contrast, for the local governments, when the initial probabilities are 0.7, trend of local governments curve is similar to that of the polluting enterprises. However, when the initial probabilities are 0.3, the trajectory of the local governments curve changes greatly, showing a trend of decline first and then rise. When the curve goes down, it means that the local governments tend to choose the strategies of not paying the ecological compensation fee to polluting enterprises; as time goes on, the curve gradually changes from state 0 to state 1, which means that the local governments finally choose the strategies of paying the ecological compensation fee to polluting enterprises.

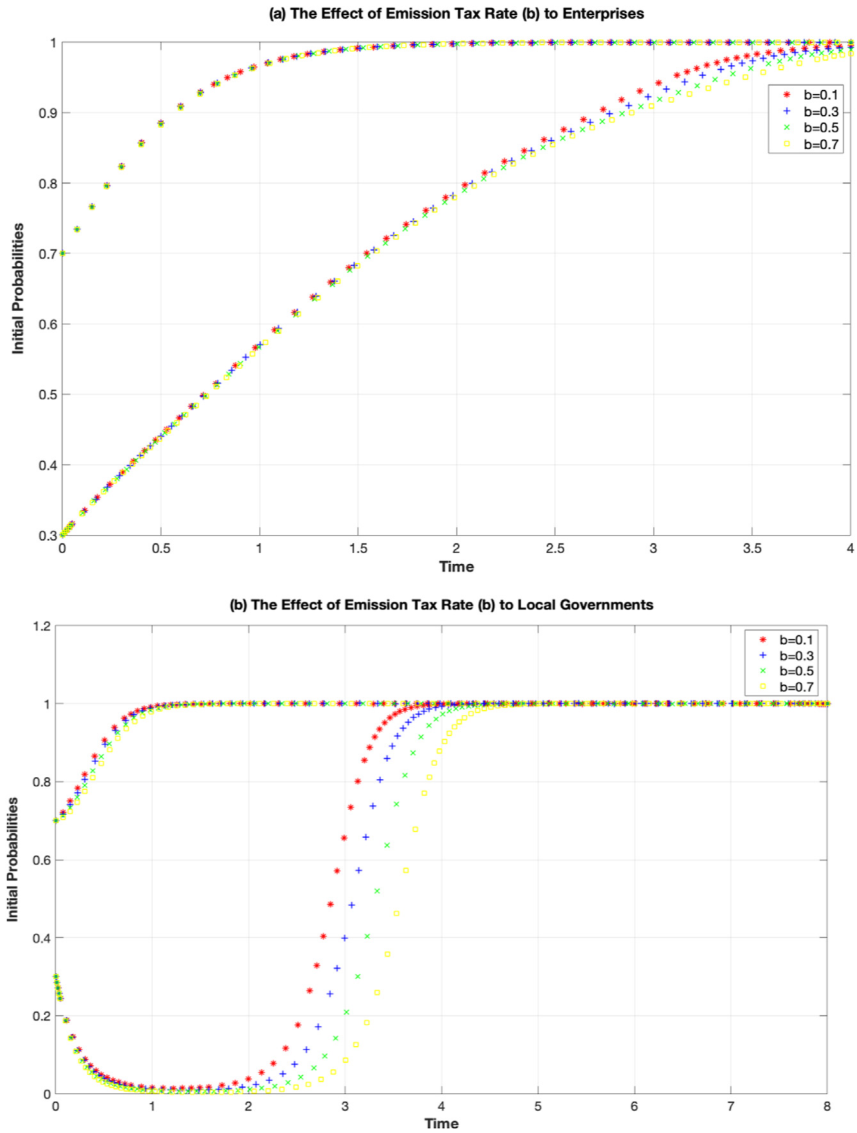

Fig. 5. The Effect of Environmental tax Rate (b) to Local Governments in the Two-party Evolutionary Game (b represents environmental tax rate).

Table 6
The settings of variable values in the simulation of the supervision ability.

Variable	R	R_1	T	E	E_1	K	H	F	D	L	b	λ	n	g
Value	40	50	9	150	120	5	5	3	15	3	0.1	1.2	0.88	0.5

Notes: R represents the total income of enterprises when they choose to protect water resources of Taihu Lake basin; R_1 represents the total income of enterprises when they choose not to protect water resources of Taihu Lake basin; T represents the total investment cost; L represents ecological compensation fee; E represents the environmental tax base when enterprises choose not to protect water resources of Taihu Lake basin; E_1 represents the environmental tax base when enterprises choose to protect water resources of Taihu Lake basin; K represents the supervision cost of local governments; H represents the social benefits of local governments; F represents the fines; D represents the reputation loss of local governments; b represents the environmental tax rate; λ represents people's avoidance degree of losses; n represents the marginal decreasing degree of the value function; $g$represents the proportion of local governments' actual payment to enterprises of ecological compensation fee; v represents the value function.

4.3. Environmental tax rate

To reflect the impact of the environmental tax rate on the system, we regard the environmental tax rate and the initial probabilities as variables, and set the values of other variables and finally simulate the system. The setting values of variables are shown in Table 5. Under the above setting, the changing process of replicated dynamic system is shown in Fig. 5.

According to Fig. 5, we can find that the curve of environmental tax rate is similar to that of ecological compensation fee for local governments and polluting enterprises. The system is stable in state 1, no matter what the initial probabilities are. At this time, polluting enterprises choose the strategies of protecting water resources, and the local governments choose the strategies of paying ecological compensation fee to polluting enterprises. For polluting enterprises, the impact of environmental tax rate is relatively small, regardless of the initial probabilities. For the local governments, under the high initial probabilities, the environmental tax rate has little impact on the local governments' strategic choice, but under the low initial probabilities, the environmental tax rate has a great impact on the local governments' strategic choice. With the increase of environmental tax rate, the time for polluting enterprises and local governments to reach a stable state will be longer. When the initial probabilities of local governments are low, this is particularly obvious.

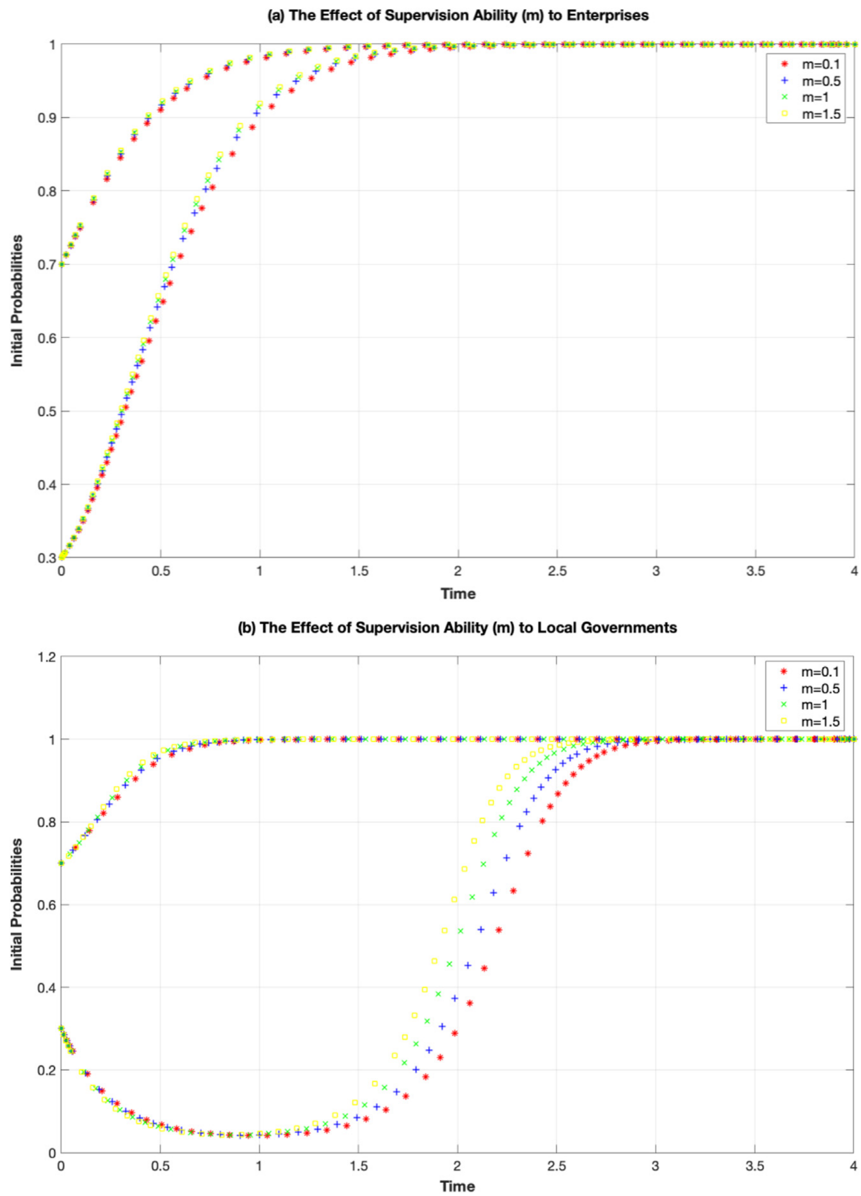

Fig. 6. The Effect of Supervision Ability (m) to Local Governments in the Two-party Evolutionary Game (m represents supervision ability).

Table 7
The settings of variable values in the simulation of marginal decreasing degree of value function.

Variable	R	R_1	T	E	E_1	K	H	F	D	L	b	λ	m	g
Value	40	50	9	150	120	5	5	3	15	3	0.1	1.2	0.5	0.5

Notes: R represents the total income of enterprises when they choose to protect water resources of Taihu Lake basin; R_1 represents the total income of enterprises when they choose not to protect water resources of Taihu Lake basin; T represents the total investment cost; L represents ecological compensation fee; E represents the environmental tax base when enterprises choose not to protect water resources of Taihu Lake basin; E_1 represents the environmental tax base when enterprises choose to protect water resources of Taihu Lake basin; K represents the supervision cost of local governments; H represents the social benefits of local governments; F represents the fines; D represents the reputation loss of local governments; b represents the environmental tax rate; m represents he supervision ability of local governments; λ represents people's avoidance degree of losses; $g$represents the proportion of local governments' actual payment to enterprises of ecological compensation fee; v represents the value function.

4.4. Supervision ability

In order to reflect the impact of the supervision ability on the replicated dynamic system, we take the supervision ability and initial probabilities as the variables and simulate the system. The settings of other variable values in the system are listed in Table 6. Under the setting of variable values, the changing process of replicated dynamic system is shown in Fig. 6.

According to Fig. 6, the change trend of the curve is similar to that of ecological compensation fee and environmental tax rate. The polluting enterprises and local governments are stable at the state 1. In this situation, the polluting enterprises choose to protect water resources and the local governments choose to pay the ecological compensation fee to polluting enterprises. For polluting enterprises, although the local governments' supervision ability has little impact on polluting enterprises, it can also be found that when

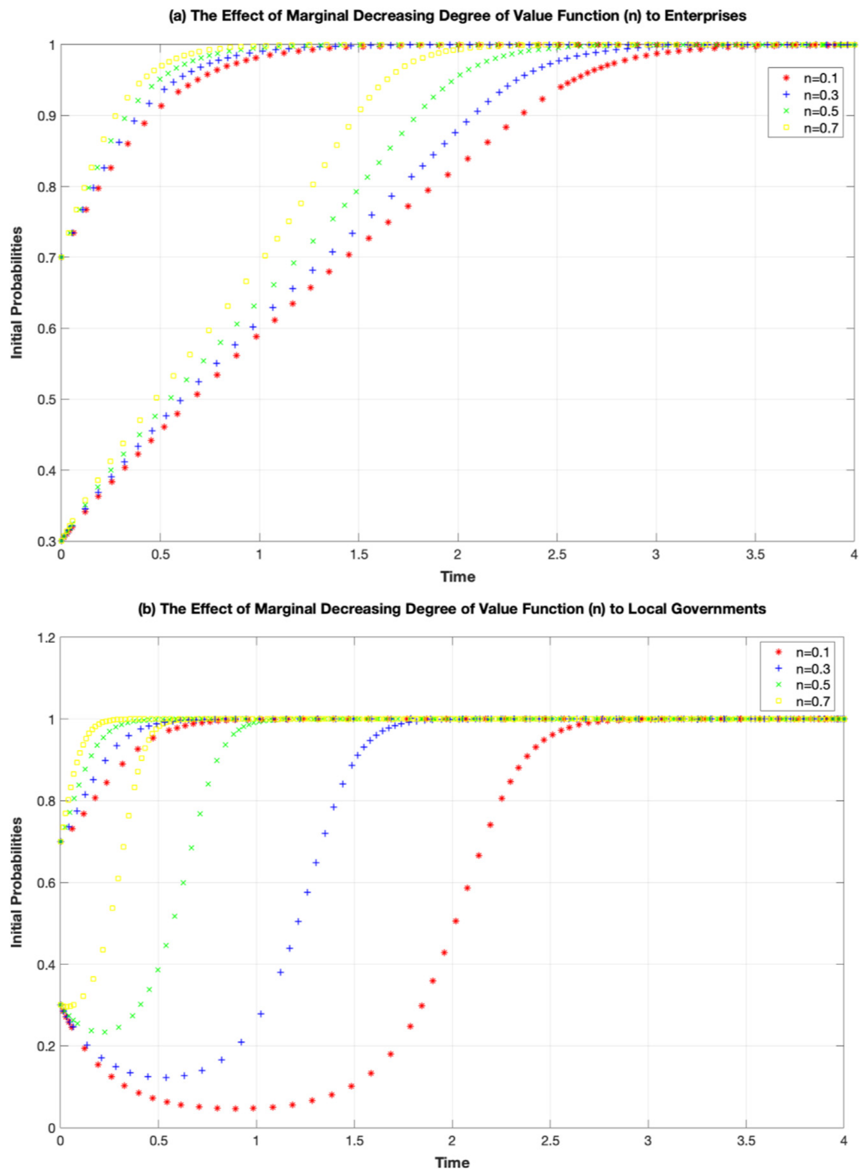

Fig. 7. The Effect of Marginal Decreasing Degree of Value Function (n) in the Two-party Evolutionary Game (n represents marginal decreasing degree of value function).

the local governments' supervision ability increase, the time for polluting enterprises to reach a stable state is slightly shortened, regardless of the initial probabilities. For the local governments, when the initial probabilities are high, the change of the local governments' supervision ability has little impact on itself, but it can be found that with the increase of the local governments' supervision ability, the time for the local governments to reach stable state 1 is slightly shorter. When the initial probabilities are low, the change of the local governments' supervision ability has a great influence on itself, and it first approaches to state 0, then gradually increases, stable at state 1 finally.

4.5. Marginal decreasing degree of value function

We simulate the marginal decreasing degree of value function to show its influence on the system. In addition to the marginal decline of the value function and initial probabilities, other variable values are set as shown in Table 7. Under this setting, the change process of marginal decreasing degree of value function is shown in Fig. 7.

According to Fig. 7(a), no matter what the initial probabilities of the polluting enterprises are, the polluting enterprises are ultimately stable in state 1, indicating that they will ultimately choose the strategies of protecting water resources and using new sewage treatment technology. And when the marginal decreasing of value function is larger, the faster the polluting enterprises reach stable state. According to the prospect theory, this shows that polluting enterprises are very sensitive to the perceived utility of profits and losses. With the increase of the marginal decreasing degree of value function, the psychological gap between the profits and losses of the polluting enterprises also increases. Based on Fig. 7(b), we can find that the local governments will ultimately choose to pay ecological compensation fee, and stable in state 1, regardless of the initial probabilities. Meanwhile, the increase of marginal decline degree of value function will lead to a significant reduction in the time for the local governments to reach a stable state. However, when the initial probabilities are high, the speed of the local governments to reach stable state will be faster than that with the low initial probabilities.

5. Discussion

In order to control cross regional water pollution, various countries have used watershed ecological compensation mechanism. However, the current watershed ecological compensation mechanism constructed by various countries mainly takes the governments as the implementation subject, but does not consider the polluting enterprises, so it is difficult to implement watershed ecological compensation mechanism for a long time. Therefore, how to attract polluting enterprises to join watershed ecological compensation and coordinate the relationship between polluting enterprises and local governments has become an important link to effectively promote the long-term implementation of watershed ecological compensation mechanism and realize the sustainable protection of water environment.

5.1. Initial probabilities

Based on the analysis of section 3.4, the initial probabilities have an important influence on the final stable state of the system. The initial probabilities can reflect the preferences and tendentiousness of the players for different strategies, and also can show the initial psychological states of the players. When the initial probabilities are high, it means that the polluting enterprises are willing to choose to protect the water resources, and the local governments are willing to choose the strategies of paying ecological compensation fee to polluting enterprises. In this case, both sides of the game will reach a stable state quickly. On the contrary, when the initial probabilities are low, although the two sides of the game can reach the best stable state under certain constraints, the time consumed is obviously increased. Therefore, it is necessary to improve the initial cooperation probability between polluting enterprises and local governments, that is, to improve their cooperation willingness and cooperation consciousness, so as to realize the stable implementation of the compensation mechanism and quickly achieve the purpose of protecting water resources.

5.2. Ecological compensation fee

According to the simulation results of section 4.2, the effect of ecological compensation fee on polluting enterprises is weak, no matter what the initial probabilities of polluting enterprises are. Even when the ecological compensation fee increases to 100, the incentive effect is still not obvious. While the impact of ecological compensation fee on local governments is only obvious when the initial probabilities of local governments are low. Therefore, the ecological compensation fee is not the most important factor to promote the polluting enterprises to join in watershed ecological compensation mechanism to protect water resources.

Ecological compensation fee, as a reward for polluting enterprises to use new sewage treatment technology to reduce pollution, cannot achieve an obvious effect at this stage. This is because when polluting enterprises compare the ecological compensation fee with the original profit before emission reduction, it is found that the profit before emission reduction will be significantly greater than the ecological compensation fee it receives. Therefore, the polluting enterprises are less sensitive to ecological compensation fee. Meanwhile, the increase of ecological compensation fee cannot promote polluting enterprises to protect water resources, but it needs to be maintained in a stable state without missing. But for local governments, the allocation of ecological compensation fee is a certain expenditure. When the initial probabilities of the local governments are high, it means that the local governments are always willing to reward polluting enterprises to protect water resources, so the increase of ecological compensation fee has little impact on local governments. However, when the initial probabilities of local governments are low, the increase of ecological compensation fee will have a greater impact on the choice of its strategy, such as the extension of time to reach a stable state, periodic changes in the curve, etc. Meanwhile, we can also find an interesting phenomenon. When the initial probabilities are low, with the increase of the ecological compensation fee, the local governments have experienced the transition process from never paying to paying the compensation fee, and the time to reach the stable state is gradually shortened. This shows that the higher the compensation fee, the greater the loss of local governments. When the willingness of local governments to participate in the mechanism is low, the appropriate increase of ecological compensation fees can force them to join the mechanism.

5.3. Environmental tax rate

Based on the simulation results of section 4.3, for polluting enterprises, when the initial probabilities are high, the environmental tax rate has little impact on them; when the initial probabilities are low, the increase of the environmental tax rate leads to the increase of the time for polluting enterprises to reach a stable state. For the local governments, no matter what the initial probabilities are, the increase of environmental tax rate will prolong the time for the local governments to reach a stable state, but the impact is more obvious under the low probabilities.

When the initial probabilities are low, we can also find an interesting phenomenon. For polluting enterprises, the increase of environmental tax rate means that polluting enterprises have to pay more to the local governments, so polluting enterprises should shorten the time to reach a stable state, and then reduce the payment of emissions. However, under the low probabilities, the polluting enterprises can reach the stable state for a longer time under the higher environmental tax rate. This means that compared with the emission fees paid by polluting enterprises, polluting enterprises prefer to get more profits from more emissions, because the profits will be far greater than the emission fees paid. This is consistent with the business thinking of some polluting enterprises around the world, especially in developing countries. At present, governments all over the world use the way of levying environmental tax to limit the emission of enterprises. Such legal compulsion can help to improve the environmental awareness of polluting enterprises and promote their emission reduction. However, the increase of environmental tax rate means that polluting enterprises will pay more pollution charges in the future. According to the prospect theory, polluting enterprises are risk seekers at this time. They hope to avoid government regulation and obtain more excess profits while discharging excessive pollutants. Therefore, the increase of environmental tax rate cannot accelerate the polluting enterprises to reach a stable state.

For the local governments, their interest demand is to obtain the maximum benefits, including economic benefits, ecological benefits and social benefits. In the past, all countries in the world have given priority to economic benefits, but the awareness of ecological environment protection is weak. At this time, even if the environmental tax rate increase, the local governments will still tend to pursue the development of local economy and ignore the protection of ecological environment, so it will tend to be stable at 0. However, with the emergence of ecological crisis and the improvement of awareness of the importance of ecological environment, governments have to pay attention to ecological benefits. Therefore, the local governments gradually changed from stable state 0 to stable state 1. Because the local governments pursue the maximum total benefit, it prolongs the time of reaching stable state 1 in the process of coordinating economic benefit and ecological benefit. The change of decision-making behavior of local governments can be obtained from Fig. 5(b).

5.4. Government participation and supervision ability

According to section 3.4, we can find that there are two possible stable points, E_1 and E_4. This means that if the local governments don't supervise the polluting enterprises, polluting enterprises will choose the strategies of not protecting water resources, and then discharge a large number of untreated sewages into the basin, which is one of the reasons for the frequent occurrence of cross regional water pollution. It shows that the local governments' supervision of polluting enterprises is conducive to the implementation of watershed ecological compensation system and the treatment of cross regional water pollution. In addition to the participation of local governments, their supervision ability also plays an important role. The local governments' supervision ability indicates whether the local governments can effectively supervise the polluting enterprises' behaviors of polluting water resources. The simulation results of section 4.4 show that no matter what the initial probabilities are, the improvement of the local governments' supervision ability will shorten the time for the system to reach stable state. For polluting enterprises, the improvement of the government's supervision ability shows that the local governments are more likely to find out whether the polluting enterprises discharge excessive sewage, and reduce the possibility of polluting enterprises escaping punishment. For the local governments, the improvement of supervision ability means that the local governments need to invest more cost in the establishment of water quality testing equipment, supervision system and related management personnel's expenses. In order to reduce the expenditure for improving the supervision ability, the local governments will reach a stable state as soon as possible. On the issue of water environment protection, it has reference value for understanding the behavior changes between governments and polluting enterprises.

5.5. Marginal decreasing degree

The marginal decreasing degree of the value function indicates the psychological expectation of the decision-maker for the profits and losses caused by different strategies. The greater the value of marginal decreasing degree, the higher the psychological expectation of profits and losses, which will affect the decision-maker's attitude towards risk.

According to the prospect theory, the marginal decreasing degree of value function reflects the decision maker's preference for risk. When the marginal decreasing degree of value function increases, it means that the decision-maker's preference for risk increases, and the decision-maker may face smaller profits or greater losses. When the initial probabilities are high, the polluting enterprises tend to choose the strategies of protecting water resources, and then they can get the ecological compensation fee from the local governments as reward. However, the allocation of ecological compensation fee is lagged and policy changes may lead to less compensation for enterprises. This results in that even if the marginal decreasing degree of value function increases and the polluting enterprises become a risk preference, the small fluctuation of future profits can only have a small impact on the time of the polluting enterprises reaching a stable state. On the contrary, when the initial probabilities are low, polluting enterprises tend to choose the strategies of not protecting water resources, and then increase the discharge of sewage. At this time, polluting enterprises may face fines from the local governments, which is a possible loss for polluting enterprises in the future. According to the prospect theory, when the marginal decreasing degree of value function increases, the risk preference of polluting enterprises increases, and the future loss increases, then it should shorten the time for polluting enterprises to reach a stable state. However, this is the opposite of our simulation results (Fig. 7(a)). The reason is that the prospect theory is usually for short-term individual decision-making, while the relative expected utility theory is for long-term group decision-making. Therefore, in the short term, when the marginal decreasing degree of value function increases, there will be some individuals in the group of polluting enterprises making corresponding decisions according to the prospect theory, that is, under the risk of fines, they will still extend the time to reach a stable state. But, in a long term, the group of polluting enterprises make decisions according to the expected utility theory and finally stabilize in state 1. When the marginal decline increases, the time for them to reach a stable state is shortened, so as to minimize the possibility of fines and reduce future losses.

For the local governments, we can get similar results. However, when the initial probabilities are low, the effect of marginal decreasing degree on the local governments is more significant. According to Fig. 7(b), the increase of marginal decreasing degree will obviously shorten the time for the local governments to reach a stable state. It shows that under the low initial probabilities, the local governments cannot pay ecological compensation fee to the polluting enterprises, which reduces the incentive of polluting enterprises to protect the water resources. When the marginal decreasing degree increases, the local governments may face serious water pollution problems, which leads to the accountability of local governments officials. In the face of possible losses in the future, the local governments' psychological expectation for losses will gradually increase. In order to avoid a large number of losses, the local governments will choose to reach a stable state as soon as possible and continue to pay ecological compensation fee to polluting enterprises.

5.6. Limitation and future work

In this paper, although we study the decision-making behaviors and main influencing factors between the polluting enterprises and the local governments in Taihu Lake Basin on the implementation of watershed ecological compensation system to solve the problem of cross regional water pollution, there are some limitations: (1) The difference of ecological compensation system in different regions may affect the system. In this paper, Taihu Lake Basin is regarded as a whole, in which all polluting enterprises and local governments constitute two groups respectively, but they are distributed in different provinces and cities. Because Taihu Lake basin includes Jiangsu Province, Zhejiang Province, Anhui Province and Shanghai City, they have introduced the watershed ecological compensation system of each province and city. However, the watershed ecological compensation systems in different provinces and cities are different, so it may have an impact on the system analysis; (2) There may be mixed effects of different variables on the system. In this paper, we analyze the influence of each independent variable on the system (initial probabilities, ecological compensation fee, environmental tax rate, supervision ability and marginal decreasing degree of value function), and also analyze the mixed impact of initial probabilities and other variables on the system. However, we do not analyze whether variables (ecological compensation fee, environmental tax rate, supervision ability and marginal decreasing degree of value function) have a comprehensive impact on the system.

In the future research, we will introduce the multi-agent analysis method to study the differential compensation mechanism between the governments and polluting enterprises in different provinces, and compare with the research results of this paper to find out the similarities and differences between the differential ecological compensation mechanism and the overall ecological compensation mechanism, and then build a more reasonable compensation mechanism to achieve the protection and sustainable development of water resources in the basin. In addition, we will conduct empirical research on different variables through questionnaire survey and econometric methods in the future to determine the actual impact of each variable on watershed ecological compensation. At the same time, interaction factors will be set to judge the mixed effects of different variables on ecological compensation.

6. Conclusion and suggestion

6.1. Conclusion

As an important policy system to control cross regional water pollution, watershed ecological compensation has been practiced for many years in Taihu Basin. In the past, the ecological compensation system of Taihu Lake Basin was mainly studied from the level of provincial and municipal governments (Jiangsu Province, Zhejiang Province and Shanghai city). In this paper, all local governments and polluting enterprises in Taihu Lake Basin were taken as the research objects, and the ecological compensation system of Taihu Lake Basin was studied by establishing evolutionary game model based on the prospect theory from the micro level. The main conclusions of this paper are as follows:

(1) The initial probabilities have an effect on the time when the system reaches stable state, and the initial probabilities and other variables have a joint effect on the system.
(2) Ecological compensation fee has little influence on the polluting enterprises, but has great influence on the decision-making behaviors of local governments with low initial probabilities.
(3) The impact of environmental tax rate on polluting enterprises is small, but interestingly, its increase will significantly prolong the time for local governments with low initial probabilities to reach a stable state.
(4) The increase of supervision ability will speed up the system to a stable state.
(5) The marginal decreasing degree of value function has more influence on the local governments than on the polluting enterprises, and its increase will obviously shorten the time when the system reaches stable state.

It is of great significance to construct a long-term and sustainable watershed ecological compensation mechanism for the protection of water resources and sustainable development. First of all, at this stage, in order to establish a sustainable watershed ecological compensation mechanism, local governments and polluting enterprises should participate together, and the focus should be on improving their ecological protection awareness and forming ecological benefit sharing mechanism. Improving the awareness of ecological protection can promote the formation of a higher awareness of cooperation between local governments and polluting enterprises, which helps the system quickly achieve a stable state of sustainable protection of water resources. On the one hand, the formation of ecological benefit sharing mechanism can make up for the defect that the ecological compensation funds allocated by the governments are not attractive to polluting enterprises, and can reduce the environmental risks caused by the instability of environment and policies; on the other hand, it can reduce the financial pressure of local governments and complete the environmental protection tasks assigned by the superior government at the same time. Secondly, the improvement of environmental supervision ability of local governments is more conducive to achieve the goal of sustainable protection of water environment. Therefore, improving the ecological protection awareness of stakeholders in the basin, forming the ecological benefit sharing mechanism and improving the environmental supervision ability of the governments will be conducive to the formation of the sustainable watershed ecological compensation mechanism. It can not only protect the water resources and realize the sustainable development, but also has an important reference value for other regions to construct watershed ecological compensation mechanism.

6.2. Suggestion

According to the analysis of this paper, some suggestions are given to local governments and polluting enterprises in Taihu Lake Basin: (1) the local governments should increase the supervision skills for polluting enterprises, including the construction of supervision system, the improvement of monitoring technology, the increase of supervision frequency, etc.; (2) the local governments should continue to promote the implementation of environmental protection tax, and promote the polluting enterprises to reduce sewage discharge; (3) the local governments should devote the whole watershed ecological compensation fee allocated by the central government to the watershed ecological protection; (4) the local governments should encourage polluting enterprises to participate in the implementation of the watershed ecological compensation system and seek long-term incentive measures.

CRediT authorship contribution statement

Juqin Shen: Conceptualization, Methodology. **Xin Gao:** Conceptualization, Methodology, Writing - original draft. **Weijun He:** Conceptualization, Methodology. **Fuhua Sun:** Writing - review & editing. **Zhaofang Zhang:** Writing - review & editing. **Yang Kong:** Writing - review & editing. **Zhongchi Wan:** Writing - review & editing. **Xin Zhang:** Validation. **Zhichao Li:** Software. **Jingzhe Wang:** Visualization. **Xiuping Lai:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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